DIRECTIONAL BIAS OF TAO DAILY BUOY WIND VECTORS IN THE CENTRAL EQUATORIAL PACIFIC OCEAN FROM NOVEMBER 2008 TO JANUARY 2010

Ge Peng[1*], Jean-Raymond Bidlot[2], H Paul Freitag[3], and Carl J Schreck III[1]

[1]*Cooperative Institute for Climate and Satellites, North Carolina (CICS-NC), North Carolina State University and NOAA's National Climatic Data Center (NCDC), 151 Patton Ave, Asheville, North Carolina, USA*
**Email:* ge.peng@noaa.gov
[2]*ECMWF, Shinfield Park, Reading, Berkshire, RG2 9AX, UK*
[3]*NOAA's Pacific Marine Environmental Laboratory, 7600 Sand Point Way NE, Seattle, Washington, USA*

ABSTRACT

This article documents a systematic bias in surface wind directions between the TAO buoy measurements at 0°, 170°W and the ECMWF analysis and forecasts. This bias was of the order 10° and persisted from November 2008 to January 2010, which was consistent with a post-recovery calibration drift in the anemometer vane. Unfortunately, the calibration drift was too time-variant to be used to correct the data so the quality flag for this deployment was adjusted to reflect low data quality. The primary purpose of this paper is to inform users in the modelling and remote-sensing community about this systematic, persistent wind directional bias, which will allow users to make an educated decision on using the data and be aware of its potential impact to their downstream product quality. The uncovering of this bias and its source demonstrates the importance of continuous scientific oversight and effective user-data provider communication in stewarding scientific data. It also suggests the need for improvement in the ability of buoy data quality control procedures of the TAO and ECMWF systems to detect future wind directional systematic biases such as the one described here.

Keywords: Systematic bias, Data quality, Winds, TAO buoy, ECMWF model

1 INTRODUCTION

The Tropical Atmosphere Ocean (TAO)/Triangle Trans-Ocean Buoy Network (TRITON) moored buoy array in the tropical Pacific Ocean began as a major contribution to the 10-year (1985-1994) Tropical Ocean-Global Atmosphere (TOGA) Program (McPhaden, 1993; McPhaden, Busalacchi, Cheney, Donguy, Gage, Halpern, et al., 1998; McPhaden, Busalacchi, & Anderson, 2010). Tropical moored arrays are also deployed in the Atlantic (Prediction and Research Moored Array in the Tropical Atlantic, PIRATA, Bourlès, Lumpkin, McPhaden, Hernandez, Nobre, Campos, et al., 2008) and Indian (Research Moored Array for African-Asian- Australian Monsoon Analysis and Prediction, RAMA, McPhaden, Meyers, Ando, Masumoto, Murty, Ravichandran, et al., 2009) Oceans. TAO/TRITON is presently comprised of 67 surface buoys, five of which are enhanced to measure surface heat, momentum, and moisture flux as a part of OceanSITES, a global network of open-ocean sustained time series sites as an integral part of the Global Ocean Observation System (http://www.oceansites.org) that strives to provide sustained high-quality reference observations to the international user community.

The versatility and utility of tropical moored buoy array data have exceeded the originally designed scope of improving detection, understanding, and prediction of climate variability on seasonal to interannual time scales related to the El Niño-Southern Oscillation (ENSO) (McPhaden, 1999; McPhaden, Delcroix, Hanawa, Kuroda, Meyers, Picaut, et al., 2001; McPhaden, Busalacchi, & Anderson, 2010). For example, the TAO buoy data have long been utilized in calibrating model functions for deriving satellite wind speeds or wind vectors (e.g., Dunbar, Hsiao, & Lambrigtsen, 1991; Wentz, 1997; Stoffelen, 1998). In addition to being assimilated in model predictions and re-analyses, the buoy measurements are also valuable in evaluating products from models and satellites and providing error or uncertainty estimates for those products (e.g., Freilich & Dunbar, 1999; Mears, Smith, & Wentz, 2001; Ebuchi, Craber, & Caruso, 2002; Abdalla, Janssen, & Bidlot, 2011; May & Bourassa, 2011; Peng, Zhang, Frank, Bidlot, Higaki, Stevens, et al., 2013). This process is beneficial to both buoy array operators and data users -

instrumental bias revealed by satellite data have led to TAO instrument improvement (Dickinson, Kelly, Caruso, & McPhaden, 2001; Freitag, O'Haleck, Thomas, & McPhaden, 2001).

Peng, Zhang, Frank, et al. (2013) revealed a systematic directional bias for year 2009 between five wind products and the TAO buoy located at 0°, 170°W in the central equatorial Pacific with the World Meteorological Organization (WMO) Identification Number 51010 (WMO 51010 hereafter), comparing collocated winds at a total of 11 OceanSITES locations (Figure 1, the WMO 51010 site is noted in the figure). This wind directional bias was slightly product-dependent, ranging from 9.9 to 13.9 degrees with a mean of about 10 degrees and biases from all five products significant at the 95% confidence level (Figure 2).

Winds from WMO 51010 are routinely assimilated into operational models, analyses, and re-analyses and used extensively in validating NWP model and satellite wind products. On the other hand, winds from the European Center for Medium range Weather Forecasting (ECMWF) analysis and forecast are also widely used to generate or validate satellite-based products or other model-based products. Thus, it is important to explore the source of the systematic bias at this location.

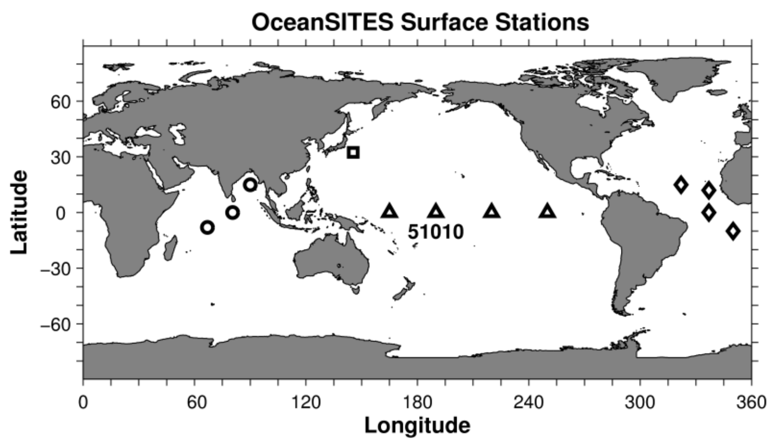

Figure 1. Location of the OceanSITES surface buoys including RAMA (circles), KEO (square, Kuroshio Extension Observatory), TAO (triangles), and PIRATA (diamonds) buoys (adapted from Peng, Zhang, Frank, et al., 2013). The WMO 51010 site is noted in the figure.

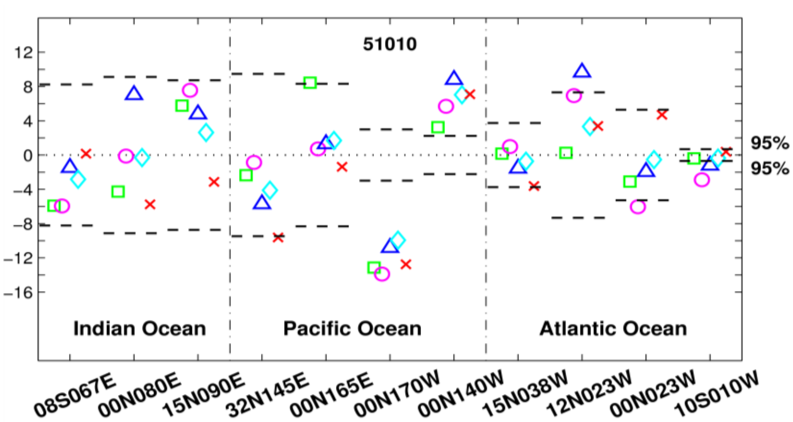

Figure 2. Directional biases of 2009 daily winds between the OceanSITES winds and five wind products (adapted from Peng, Zhang, Frank, et al., 2013). The wind products include short-range forecasts from the German Weather Service "Deutscher Wetterdienst" (DWD), denoted by squares, ECMWF (circles), and the Japan Meteorological Agency (JMA, triangles), National Centers for Environmental Prediction (NCEP) Climate Forecast System Reanalysis (CFSR), denoted by diamonds, and the NCDC blended ocean surface winds (crosses) (see Peng, Zhang, Frank, et al., 2013 for more details). Weak winds (wind speed < 3 m/s) are not included in the calculations of

directional bias. Bias values outside of the dashed lines for each station are significant at the 95% confidence level. The values of bias for WMO 51010 are denoted in the figure. The bias thresholds for the 95% confidence level are proportional to the ratio between the standard deviation of the time series and the square root of the number of records. The large variation of the bias thresholds shown in this figure is largely associated with the variation of the wind direction standard deviation.

2 TAO/TRITON BUOY DATA OUTLINE

TAO, PIRATA, and most RAMA surface moorings are instrumented with ATLAS (Autonomous Temperature Line Acquisition System) instrumentation (Milburn, McLain, & Meinig, 1996). Data are telemetered to shore via the Argos satellite system. Service Argos, Inc. distributes the data directly to the National Oceanic and Atmospheric Administration (NOAA)'s Pacific Marine Environmental Laboratory (PMEL) and NOAA's National Data Buoy Center (NDBC). It also places the data on the Global Telecommunications System (GTS) for use by international weather and climate forecast centers. Near real-time ATLAS data quality control (QC) is routinely performed on a daily, weekly, and monthly basis, with specific procedures for each data type (http://www.pmel.noaa.gov/tao/proj_over/qc.html).

Wind direction is measured by combining the apparent wind direction from the anemometer vane and the orientation of the buoy from a compass. Checks are made for non-varying compass or vane values and daily wind direction changes of more than 90° in one day. Weekly mean wind direction is compared to Comprehensive Ocean-Atmosphere Data Set (COADS) climatology and noted when differences are greater than 30°. NCEP provides weekly statistics of mean, standard deviation, and Root Mean Square (RMS) differences between zonal and meridional buoy wind components and its Medium Range Forecast (MRF) version of the Global Forecast System (GFS) model.

Data quality indices are assigned to each data point on a scale of 1 to 5. Near real-time data are assigned an index of 2, unless the QC process indicates a clear bias or an abnormal level of noise for which an index of 4 is assigned. A quality index of 3 is given to data that have been adjusted to lower observed bias or noise. Missing or flagged data are assigned an index of 5. After recovery of a buoy, higher temporal data are available from the instrument's memory, and similar quality control procedures are applied. Working sensors are recalibrated when returned to PMEL. If sensor drift is within expected limits and the high-resolution data pass inspection, the data are assigned a quality index of 1. Based on post-recovery calibrations of compasses and vanes, Freitag, O'Haleck, Thomas, et al. (2001) estimated ATLAS wind direction accuracy to be between 5.0° and 7.8°, the latter being due to bias in vane calibrations performed before 2001. Elimination of the vane error was expected to result in wind direction accuracy nearer the lower value. The compasses analysed in 2001 have since gone out of production, and newer compasses have proven to have larger error statistics than the previous sensors. Initial analysis suggests that ATLAS wind direction accuracy remains between about 5° and 8°, depending on the type of compass used. The data quality index is lowered to 4 if the RMS difference of the combined compass and vane wind direction calibrations is greater than 10°.

3 ECMWF MODEL SYSTEM OUTLINE

The ECMWF operational global atmospheric model is a hydrostatic spectral model based on the ECMWF Integrated Forecasting System. The latest operational resolution since January 2010 is T1279, roughly equivalent to a grid point spacing of 16 km. Prior to January 2010, it had a spectral resolution of T799 (25 km) with 91 levels in the vertical from about 10 m to 0.01 hPa (Untch, Miller, Hortal, Buizza, & Janssen, 2006). ECMWF provides the international user community with its analysis, short-range, and long-range forecasts.

The initial conditions for the forecasts are obtained from the advanced four-dimensional variational (4DVAR) data assimilation system (Bauer, Geer, Lopez, & Salmond, 2010). Buoy data are assimilated during this process with various procedures to detect and screen erroneous or inconsistent observations (Andersson & Järvinen, 1999; Radnoti, Bauer, McNally, & Horanyi, 2012, see also http://old.ecmwf.int/research/ifsdocs/CY38r1/IFSPart2.pdf)

Tropical moored buoy observations used by ECMWF are obtained via the GTS. For the purpose of assimilation, they are combined with all observations from drifting buoys (DRIBU). The Monin–Obukhov based observation operator for 10-metre wind is used for all surface winds to bring the model winds to the actual observation height (in practice ranging from 4 to 10 m). The impact of assimilating buoy data has been demonstrated in Radnoti, Bauer, McNally, et al. (2012), albeit not specifically for TAO data.

4 DIRECTIONAL BIAS DETECTION

Figure 3 shows the time series of the 3-month running mean directional bias between WMO 51010 and the ECMWF analysis and forecasts at various leads from summer 2005 to spring 2012. The bias is generally small but tends to become larger at longer forecast leads, except for a sustained bias of about 10° that lasted from November 2008 until January 2010. No significant changes were made to the model during this period (ECMWF, 2008) so the bias is unlikely to be model-related. Furthermore, having been observed in two other NWP forecasts, the latest NCEP reanalysis, and a satellite-based wind product for 2009 (Peng, Zhang, Frank, et al., 2013), the directional bias between WMO 51010 and ECMWF as shown in Figures 2 and 3 is unlikely to be just due to changes in the ECMWF model.

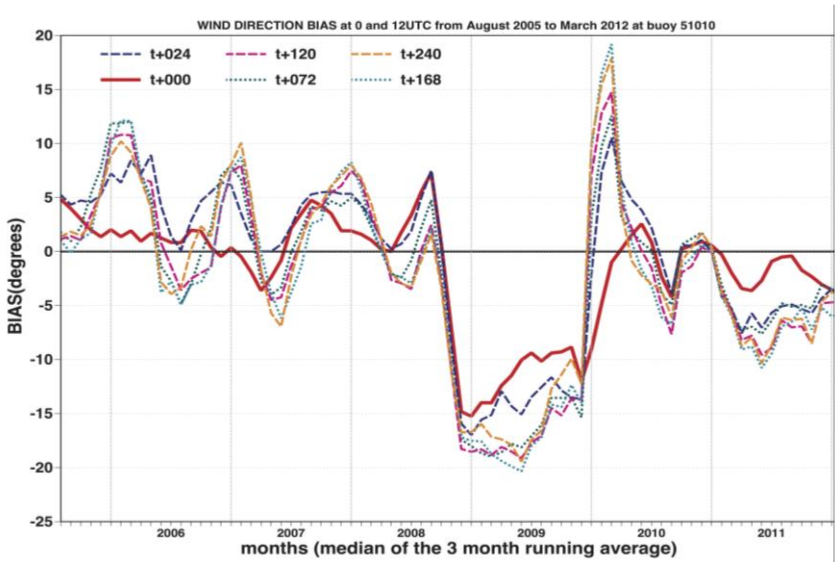

Figure 3. Time series of the 3-month running mean ECMWF analysis and forecasts wind directional bias at the WMO 51010 buoy location from August 2005 to March 2012.

A number of other factors could have caused the systematic bias including transmission errors and instrument performance (damage to sensors, calibration drift). A communication error during the flow of data and processed products could result in faulty data on the receiving end. The wind direction bias noted here was limited to only a few locations (Peng, Zhang, Frank, et al., 2013; also see Figure 2 and Table 1). Because data from all moorings follow identical communication pathways, it is highly unlikely that communication errors caused the bias. If there was a random glitch during the transmission process for this site any time during this period, it was most likely to be visible and short lived. Figure 4a shows the time series of wind directions computed from the 7-day running mean of WMO 51010 6-hourly wind components from January 2008 to January 2011. There was no apparent fluctuation in wind directions throughout 2008. However, there was a noticeable positive shift in the buoy's wind direction (red line) that occurred in early November of 2008. No such shift occurs in the ECMWF model data (black), which results in a large model–buoy bias (Figure 4b), consistent with Figure 3. The wind direction becomes more variable and shifts sharply lower in early 2010 before becoming less fluctuating again. This final shift coincides with the replacement of the sensors in February 2010.

The similar behaviour, i.e., sudden wind direction shift of WMO 51010 buoy winds in early November 2008, was not observed for surface wind vectors from the NCEP GFS analysis or at near-by buoy locations (figure not shown), indicating that this systematic bias pertains to the WMO 51010 site only for the time period when this particular buoy was deployed but is not limited to the winds between the buoy and ECMWF.

We examined numerous satellite estimates of clouds, winds, and outgoing longwave radiation (OLR) and did not find any obvious severe weather events that could have damaged the instruments. Little or no bias was observed beginning in February 2010, which is coincident with the time at which the ATLAS mooring was recovered and new instrumentation was deployed. Thus the bias was most likely due to the mooring compass or vane at this site. A post-deployment calibration check of the compass showed it to be within normal specification, but a calibration check of the vane found bias of about 15°. Subsequent inspection of the sensor indicated that the failure could cause the offset to vary with time. As the post-recovery calibration bias could not be used to confidently correct the data, the quality index for this deployment was adjusted to 4 to reflect the low data quality.

Table 1. Statistics of weekly RMS differences between tropical moored buoy wind observations and NCEP's Medium Range Forecast (0-hour) reported on November 17, 2008. Zonal (U) and meridional (V) statistics were computed by NCEP from 5105 observations at 68 moorings over a 7-day time period. Speed and direction differences were computed from U and V differences at each mooring as reported by NCEP.

	U (m/s)	V (m/s_	Speed (m/s)	Direction (degree)
Minimum	0.3	0.3	0.0	0.0
Maximum	1.9	1.9	1.9	25.0
Mean	0.9	1.0	0.5	6.6
0 170W	0.4	1.3	0.5	9.3

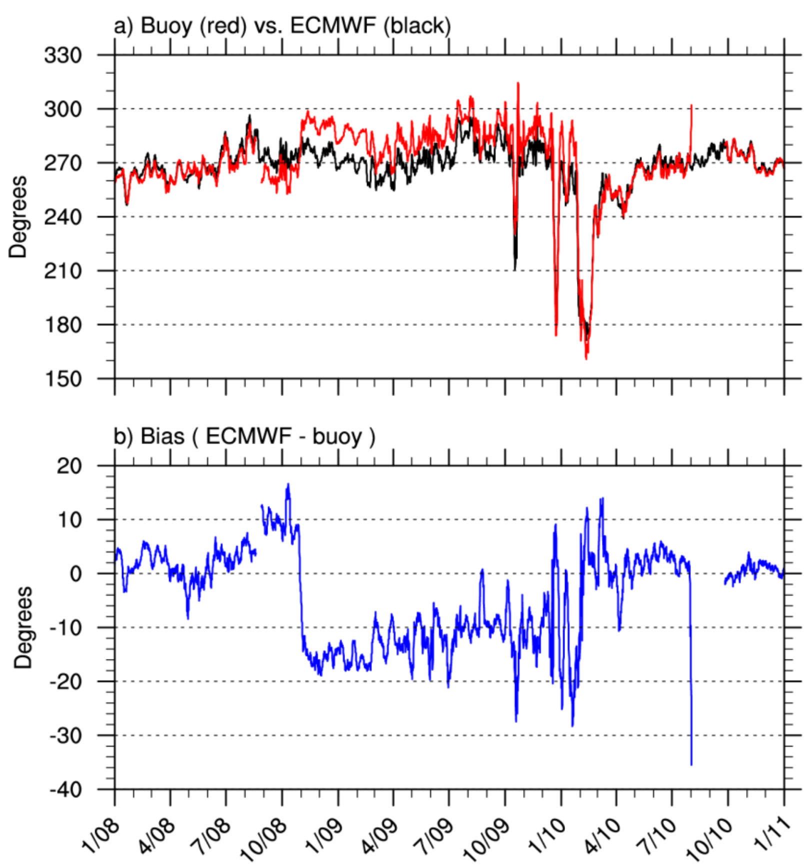

Figure 4. a) wind directions from the 7-day running means of 6-hourly wind components from ECMWF (black) and the WMO 51010 buoy (red) from January 2008 to January 2011 and b) the difference between the two. The 6-hourly buoy data are from the GTS system.

5 SUMMARY AND DISCUSSION

An anemometer vane was deployed at the WMO 51010/TAO mooring site, located at 0°, 170°W in the central equatorial Pacific, from August 24, 2008 to February 1, 2010, to measure wind speeds and directions. Utilizing analysis and forecast winds from ECMWF, a systematic buoy wind direction bias of order 10° was identified from November 2008 to January 2010 and was found to be associated with the post-recovery calibration drift of the anemometer vane at this mooring site. Unfortunately, this post-recovery calibration drift was too time-variant to be used to correct the data so the quality flag for this deployment was adjusted to 4 to reflect low data quality.

This particular occurrence is an aberration in the otherwise excellent performance of the buoy network over many years. It should not be used to undermine the importance, contributions, and necessity of maintaining this usually good-quality and widely-used in situ observational ground network. However, the fact that it did happen and has gone unnoticed until now indicates that there may be room for improvement in the current near real-time quality monitoring and post-calibration system of the buoy array.

The ATLAS mooring wind direction is measured as a combination of a compass heading and an anemometer vane. The combined RMS post-recovery calibration drift of the sensors is usually between 5° and 8°. Typical sensor failures involve an absolute failure of the compass and/or vane. Another failure mode is for the vane to be physically broken off (typically by vandals) in which case the wind direction would be biased by 180°. These sensors are individually monitored in real-time on a daily basis, and failures are easily identified by differences between mooring wind direction and climatology that exceed 30°.

In the case of WMO 51010, a calibration bias in the vane appears to have been the culprit. Such an occurrence is relatively rare given the large numbers of mooring sites and years of data provided. The observed bias of order 10° would be difficult to accurately identify during the current near real-time quality control procedures as biases in wind direction at WMO 51010 did not translate into noticeable biases in wind components. NCEP weekly statistics of mean, standard deviation, and RMS differences between zonal and meridional buoy wind components and the MRF winds did not indicate a clear bias for the WMO 51010 mooring data. For example, RMS differences reported for November 17, 2008, at WMO 51010 were not obvious anomalies compared to those at other tropical moorings (Table 1). Zonal wind RMS differences at WMO 51010 were among the smallest observed over 68 tropical mooring sites. The meridional wind RMS differences at WMO 51010 were larger than at most sites but were smaller than at 9 other sites. Wind speed and direction were not included in the NCEP report, but proxy statistics were computed from the zonal and meridional RMS differences at each mooring site. The directional bias at WMO 51010 was 9.3°, compared to a mean bias of 6.6° computed over all mooring sites for that week. Seventeen (17) sites had directional differences greater than at WMO 51010.

Although comparison with weekly MRF wind components may not clearly identify all potential systematic directional biases, additional QC procedures could enhance the ability to identify persistent biases of this magnitude. For example, it may be useful to track the number of weeks a given site exceeded a threshold bias level. In addition, large uncertainties associated with weak winds (i.e., speeds less than 3 m/s) tend to mask the potential persistent, systematic biases. For example, the maximum value of 25.0° was computed at a site for which the average ATLAS wind speed was only 1.0 m s^{-1}. Thus, caution should be taken when computing directional bias from components when the total magnitude is weak or they should be excluded from the near real-time QC and quality monitoring procedures. Automatic alert flags with additional analysis by scientific stewards could be helpful in identifying potential systematic wind directional biases of less than 30^{o}. Cross-validation with other wind products such as ECMWF or satellite-based winds may also help to uncover any persistent bias in a timely fashion. For long-term quality assurance, regular and recurring in-depth data comparison/analysis on the regional scale will be useful to identify potential issues that may be overlooked by analyses done only on the global scale.

The ECMWF data assimilation system also uses wind components as input. An extensive examination of the performance of the ECMWF quality control procedure in assimilating the WMO 51010 buoy data and potential impact of assimilating the marginal biased buoy data on ECMWF products would be valuable, but it is beyond the scope of this paper. The preliminary screening for the time period before and after the onset of this bias, however, has indicated that the ECMWF data quality control procedure did not consistently reject the WMO 51010 buoy data because of the fact that the winds are dominated by a zonal component. The bias and RMS error between the model and buoy zonal winds tend to be in the acceptable ranges or within data accuracy. The bias and RMS error of meridional winds may be large and could have been the key in detecting the discrepancy. However, large meridional bias and RMS error tend to be ignored by quality control systems because the meridional winds in the equatorial Pacific tend to be light but highly variable such as in our case.

ECMWF has recently started a comprehensive review on how to better monitor the quality of all in-situ observations, particularly in light of events like this one. The monitoring system will look at long-term statistics of individual stations to determine any significant changes to detect any potential issue sooner. Moreover, ECMWF is now in the process of producing a full reanalysis of the 20th century, making use of all available observations within a framework of a comprehensive atmosphere-ocean model system. This effort will build a database of model-observation statistics that could be used to detect past problems and further enhance the future use of data.

There is no doubt that the activities of data quality assurance/assessment/monitoring are extremely important to ensure the accuracy and usefulness of the data products. However, rapidly increasing data volumes and data latency demand have posted increasing challenges for data providers/operators/stewards and begun to push the roles and responsibility of ensuring product quality beyond the ability of data operators/providers – it has become more and more a collective effort of all stakeholders in the life cycle of data product creation, data governance including quality management, application, and improvement.

Although scientific data users are at the forefront of noticing any potential quality issue associated with a data product, it usually takes a joint effort among data users and providers/operators/stewards to identify the nature and source of the issue, as demonstrated in this case. Thus, it is important for data providers/stewards to establish a clear and easy communication channel for users to report potential quality issues and an efficient way to screen those reports promptly and collaborate with scientific data users to identify the nature and source of data quality issues. Furthermore, the descriptions of uncovered quality issues should be conveyed to users as open access, citable, and traceable articles in a timely fashion, especially for the highly utilized data and model products such as TAO and ECMWF data, to minimize redundant efforts on uncovering the same data quality issues and potential impact on the downstream product quality.

In conclusion, it is crucial to have continuous scientific oversight and effective user-data provider-user communication in stewarding long-term, high-quality environmental data products in addition to continuously improved data quality assurance and monitoring procedures to ensure and improve the maturity and usefulness of the products in the future, which will in turn benefit the user community world-wide.

6 ACKNOWLEDGEMENT

G. Peng and C.J. Schreck were supported by the NOAA/NCDC Climate Data Records Program through the Cooperative Institute for Climate and Satellites – North Carolina, under Cooperative Agreement NA09NES4400006. J.-R. Bidlot is supported by ECMWF and H.F. Freitag by NOAA/PMEL. We thank Ken Knapp for discussions on satellite images. We would also like to thank NCDC, PMEL, and ECMWF internal reviewers and DSJ editors and reviewers. Comments and suggestions from Otis Brown, Michael McPhaden, and Thomas Peterson are greatly appreciated.

7 REFERENCES

Abdalla, S., Janssen, P., & Bidlot, J.-R. (2011) Altimeter Near Real Time Wind and Wave Products: Random Error Estimation. *Marine Geodesy 34*(3-4), 393-406.

Andersson, E. & Järvinen, H. (1999) Variational quality control. *Q. J. Roy. Meteor. Soc. 125*, 697-722.

Bauer, P., Geer, A. J. , Lopez, P., & Salmond, D., (2010) Direct 4D-Var assimilation of all-sky radiances. Part I: Implementation. *Quart. J. Roy. Meteor. Soc. 136*, 1868-1885.

Bourlès B., Lumpkin, R., McPhaden, M.J., Hernandez, F., Nobre, P., Campos, E., Yu, L., Planton, S., Busalacchi, A.J., Moura, A.D., Servain, J., & Trotte, J. (2008) The PIRATA program: history, accomplishments, and future directions. *Bull. Am. Met. Soc. 89*(8), doi: 10.1175/2008BAMS2462.1.

Dickinson, S., Kelly, K.A., Caruso, M.J., & McPhaden, M.J. (2001) Comparison between the TAO buoy and NASA Scatterometer wind vectors. *J. Atmos. Oceanic Tech*. *18*, 779 – 806.

Dunbar, R.S., Hsiao, S.V., & Lambrigtsen, B.H. (1991) Science algorithm specifications for the NASA Scatterometer Project: Geophysical Algorithms. *JPL D-5610-2*, Jet Propulsion Lab., Pasadena, Calif.

ECMWF (2008) ECMWF 2008 Annual Report. ECMWF, Reading, United Kingdom, 67pp. Retrieved from the World Wide Web, July 17, 2014: http://old.ecmwf.int/publications/annual_report/2008/index.html

Ebuchi, N., Craber, H. C., & Caruso, M. J. (2002) Evaluation of wind vectors observed by QuikSCAT/Sea Winds using ocean buoy data. *J. Atmos. Oceanic Tech. 19*, 2049 – 2062.

Freilich, M. H., & Dunbar, R. S. (1999) The accuracy of the NSCAT 1 vector winds: Comparisons with National Data Buoy Center buoys. *J. Geophys. Res. 104*, 11,231 – 11,246.

Freitag, H.P., O'Haleck, M., Thomas, G.C., & McPhaden, M.J. (2001) Calibration procedures and instrumental accuracies for ATLAS wind measurements. *NOAA Technical Memorandum OAR PMEL-119*, 20 pp.

May, J.C., & Bourassa, M.A. (2011) Quantifying variance due to temporal and spatial difference between ship and satellite winds*. J. Geophys. Res*. *116*, C08013, doi:10.1029/2010JC006931.

McPhaden, M.J. (1993) TOGA-TAO and the 1991-1993 El Niño-Southern Oscillation event. *Oceanography 6*, 36 – 44.

McPhaden, M.J. (1999) Genesis and Evolution of the 1997 – 98 El Niño. *Science 283*, 950 – 954.

McPhaden, M.J., Busalacchi, A.J., Cheney, R., Donguy, J.R., Gage, K.S., Halpern, D., Ji, M., Julian, P., Meyers, G., Mitchum, G.T., & others (1998) The tropical ocean–global atmosphere (TOGA) observing 700 system: a decade of progress. *J. Geophys. Res*. *103*, 14,169 - 14,240.

McPhaden, M.J., Delcroix, T., Hanawa, K., Kuroda, Y., Meyers, G., Picaut, J., & Swenson, M. (2001) The El Niño-Southern Oscillation Observing System. In: *Observing the Ocean in the 21st Century*. Australian Bureau of Meteorology, Melbourne, Australia, 231 – 246.

McPhaden, M.J., Meyers, G., Ando, K., Masumoto, Y., Murty, V.S.N., Ravichandran, M., Syamsudin, F., Vialard, J., Yu, L., & Yu, W. (2009) RAMA: The Research Moored Array for African-Asian-Australian Monsoon Analysis and Prediction. *Bull. Am. Meteorol. Soc*. *90*, 459-480.

McPhaden, M.J., Busalacchi, A.J., & Anderson, D.L.T. (2010) A TOGA retrospective. *Oceanography 23*, 86 – 103.

Mears, C.A., Smith, D.K., & Wentz, F. (2001) Comparison of special sensor microwave imager and buoy-measured wind speeds from 1987 to 1997. *J. Geophys. 106*, 11,719 – 11,729.

Milburn, H.B., McLain, P.D., & Meinig, C. (1996) ATLAS buoy-reengineered for the next decade. In: *Proceedings of the IEEE/MTS Ocean'96*, Fort Lauderdale, FL, September 23-26, 1996, 698-702.

Peng, G., Zhang, H.-M., Frank, H.P., Bidlot, J.-R., Higaki, M., Stevens, S., & Hankins, W.R. (2013) Evaluation of various surface wind products with OceanSITES buoy measurements. *Wea. Forecasting 28*, 1281–1303. doi: http://dx.doi.org/10.1175/WAF-D-12-00086.1.

Radnoti, G., Bauer, P., McNally, A., & Horanyi, A. (2012) ECMWF study to quantify the interaction between terrestrial and space-based observing systems on Numerical Weather Prediction skill. *ECMWF Tech. Memo. 679*. ECMWF, Reading, United Kingdom, 97pp.

Stoffelen, A. (1998) Toward the near-surface wind speed: Error modelling and calibration using triple collocation. *J. Geophys. Res. 103*, 7755 - 7766, doi:10.1029/97JC03180.

Untch, A., Miller, M., Hortal, M., Buizza, R., & Janssen, P. (2006) Towards a global meso-scale model: The high-resolution system T799L91 and T399L62 EPS. *ECMWF Newsletter 108*, 6-13.

Wentz, F.J. (1997) A well-calibrated ocean algorithm for SSM/I. *J. Geophys. Res. 102*(C4), 8703– 8718.

(Article history: Received 16 May 2014, Accepted 11 July 2014, Available online 29 July 2014)